September 30, 2020

Anhydrous Ammonia Release Study

I. ACCIDENT

NTSB Number:	HMD19FR002
Location:	Beach Park, Illinois
Date:	April 25, 2019
Time:	0420 central daylight time
Vehicle:	John Deere tractor towing anhydrous ammonia applicator and trailer with dual anhydrous ammonia nurse tanks

II. VEHICLE PERFORMANCE SPECIALIST

Kevin J. Renze, Ph.D.
Vehicle Performance Engineer
Office of Research and Engineering
National Transportation Safety Board (NTSB)

1.0 INTRODUCTION

The NTSB Office of Railroad, Pipeline and Hazardous Materials Investigations requested technical support to evaluate the plumbing configuration of the dual nurse tank trailer involved in an uncontrolled release of anhydrous ammonia (AA). This study used the dual nurse tank equipment configuration and publicly available, empirical data to estimate the rate at which anhydrous ammonia was released. In addition, two nurse tank hose plumbing configurations were evaluated to quantify the expected excess flow valve (EFV) activation points. See the NTSB Accident Docket for a summary of the accident.

2.0 FACTUAL EVIDENCE

2.1 Vehicle Characteristics

The tractor, AA applicator, and dual AA nurse tank trailer are shown in Figure 1. Each tank has a capacity of 1,000 gallons. The nominal AA tank load is 85 percent or 850 gallons per tank. At the time of the accidental AA release, the farmer estimated that 30 percent of the AA remained. He also stated that about 29 acres were fertilized at a rate of 200 pounds of AA per acre. A tee connection was used to yoke the two nurse tank withdrawal hoses together. The two hoses entering the tee and the single hose exiting the tee to the trailer bulkhead each had 1-inch inner diameter hose. The width of the applicator was 32 feet.

Figure 1: Tractor, AA applicator, and dual AA nurse tank trailer

2.2 Method and Data

Anhydrous ammonia leak rates in gallons per minute (gpm) were calculated as a function of temperature for two AA tank plumbing configurations using publicly available, empirical and model data. The tank contents were assumed to be stabilized at the ambient temperature for each scenario. The AA liquid and AA vapor properties shown in Attachment 1, Figures A1.1 and A1.2 were used to determine the respective liquid/vapor density as a function of temperature as well as the pressure as a function of temperature.

The AA data and equations used to model each scenario were obtained from Reindl and Jekel, *Revisiting Refrigerant Release Estimates*, Appendix A, Technical Paper #7, International Institute of Ammonia Refrigeration (IIAR), 2016. The following Reindl and Jekel large-opening AA leak rate data were used for this NTSB study:

1. AA liquid leak rates (frozen flow) for 1.0 and 0.75 inch lines
2. AA liquid leak rates (Fauske model–equilibrium) for 1.0 and 0.75 inch lines
3. AA vapor leak rates for 1.5 inch and 1.0 inch hot gas line sheared off

These AA liquid, AA liquid/vapor, and AA vapor data correspond to the respective black and blue, red and green, and magenta and cyan solid lines shown in Attachment 2, Figures A2.1 and A2.2.

2.3 Anhydrous Ammonia Release Scenarios

Two AA dual nurse tank plumbing configurations were considered. Each 1,000 gallon tank was filled with AA to 85 percent of capacity (850 gallons) and subsequently emptied to 30 percent of that load (30 percent of 850 is 255 gallons) before the simulated release event. The data in Figures A2.1 and A2.2 are broken up into three modeling categories - liquid only, liquid/vapor, and vapor only.

2.3.1 Yoked Scenario (accident configuration)

The "yoked" scenario represents the accident nurse tank trailer configuration with dual 1,000 gallon tanks yoked together such that a 1-inch supply line from each tank is combined in a manifold to yield a single exiting 1-inch supply line that feeds the AA applicator. For simplicity, each tank is assumed to supply one-half of the AA mass flow that enters the AA applicator.

2.3.2 No Yoke Scenario (hypothetical configuration)

The hypothetical "no yoke" scenario represents a dual nurse tank trailer configuration with only one of the two 1,000 gallon tanks directly connected to the AA applicator via its 1-inch withdrawal line.

3.0 RESULTS

The data from the 1-inch, liquid/vapor model are the basis for the results that follow because agricultural AA application, in practice, involves a two-phase (liquid-vapor) flow in the region between the AA tank and the AA applicator. This is the region where the 1-inch applicator supply hose separated from the AA dual tank trailer bulkhead during the accidental AA release. The discussion in Sections 3.1 and 3.2 refer to the AA liquid/vapor data for the 1-inch line and the intersecting red, dashed, horizontal lines shown in Attachment 2, Figures A2.1 and A2.2.

3.1 Yoked Scenario (accident configuration)

On a 37 degrees Fahrenheit (°F) day, each AA tank could supply up to about 25 gpm of AA, which would be combined by the yoke plumbing to yield up to 2 times 25 equals 50 gpm of AA supplied to the applicator.

For this scenario, if the EFVs were rated at 42 ±10 percent gpm, neither EFV would be expected to close if the 1-inch supply line to the applicator accidentally disconnected. This scenario is consistent with the accident nurse tank trailer setup and the lack of activation of either nurse tank EFV after the accidental AA release.

For the yoked configuration nominal 42 gpm ± 10% EFVs to provide protection against an accidental AA release, the ambient temperature (and corresponding temperature/pressure relationship in each tank) would have to increase to between 62.5 and 76 °F, depending on the minimum gpm activation point for the more conservative EFV. Once the more conservative EFV closed (at the lower gpm activation point), the less conservative EFV (at the higher gpm activation point) would close in quick succession. This result is expected since the higher ambient temperature range in this hypothetical scenario provides ample flow rate to close the remaining EFV in the "new" nurse tank plumbing configuration, which can be equated to a single 1-inch tank supply line to the applicator (after the first EFV closes).

The yoked configuration would be expected to provide no protection against an accidental AA release for operations conducted on days when the ambient temperature is less than 62.5 °F (and conceivably no protection for days when the ambient temperature is less than 76 °F).

3.2 No Yoke Scenario (hypothetical configuration)

In the no yoke configuration (i.e., direct connection from either AA tank to the applicator), a 42 gpm ± 10% EFV would be expected to provide protection against an accidental AA release for ambient temperatures above about 22 to 33 °F, which for cold-soaked temperature environments, corresponds to AA application temperatures at or above frozen soil conditions. Frozen soil conditions prohibit AA application due to the enormous drawbar pull requirements for the applicator and the accompanying high probability of damaging the tractor and/or the applicator.

3.3 Anhydrous Ammonia Application and Estimated Release Data

Exemplar AA application data are included in Attachment 3, Figures 3.1 and 3.2. AA flow rate in gpm is plotted versus the desired nitrogen application rate in pounds per acre. Lines of constant speed in mph are shown for an assumed AA applicator width of 30 feet or 60 feet, each with an assumed AA tank pressure of 100 psi.

The molecular weight of nitrogen is 14.0067 atomic units and the molecular weight of hydrogen is 1.00784 atomic units. Therefore, the molecular weight of NH_3 is 14.0067 + 3*1.00784 = 17.0302 atomic units. Nitrogen is 14.0067/17.0302*100 = 82.2462 percent of the molecular weight of each NH_3 molecule. Each pound of nitrogen applied requires 1/.822462 = 1.2159 pounds of NH_3 so 200 pounds of AA per acre provides about 200/1.2159 = 164.5 pounds of nitrogen per acre.

If 29 acres were treated with AA prior to the accident, about 29*200 = 5,800 pounds of AA were applied. Assuming a liquid AA weight per unit volume of 39.6278 pounds per cubic foot at 37 °F and given 0.133681 cubic foot per gallon, the liquid AA weight per unit volume would be about 5.2975 pounds per gallon. The corresponding liquid nitrogen weight per gallon of AA would be about 5.2975*.822462 = 4.357 pounds. Thus, treating 29 acres with 5,800 pounds of AA would equate to consuming about 5,800/5.2975 = 1,094.9 gallons of AA.

On a volume basis, if 2*850 = 1,700 gallons of AA were originally loaded and about 1,094.9 gallons were applied, then about 1,700 – 1,094.9 = 605.1 gallons of AA (605.1/2 = 302.6 gallons per tank), or about 605.1/ 1,700*100 = 35.6 percent of the original AA load was available to release.

On a weight basis, the Conserv FS scale ticket for tank unit number 200 indicated a net AA weight of 9,260 pounds. If 5,800 pounds of AA were applied, then about 9,260 – 5,800 = 3,460 pounds of AA (3,460/2 =

1,730 pounds per tank) were available to release. This remaining AA weight equates to about 3,460/5.2975 = 653.1 gallons of AA (653.1/2 = 326.6 gallons per tank), or about 653.1/1,700*100 = 38.4 percent of the original AA load available to release.

At the time of the accidental AA release, the remaining AA volume was estimated to be 30 percent. **If 30 percent refers to the nominal AA load** (85 percent of the available 1,000 gallon volume per tank), then 0.30*0.85*1,000 = 255 gallons per tank, or a total of 255*2 = 510 gallons of AA available to release. **If 30 percent refers to the tank volume** (100 percent of the available 1,000 gallon volume per tank), then 0.30*1.00*1,000 = 300 gallons per tank, or a total of 300*2 = 600 gallons of AA available to release.

Estimated times required to release the dual AA nurse tank contents as a function of the estimated AA volume remaining are summarized in Table 1. For example, at a flow rate of 50 gpm and an initial supply of 600 gallons, the dual tank contents would be released in about 12 minutes. If the AA flow rate decreased by a factor of 2 or 3, the dual AA tank contents would be released in about 24 or 36 minutes, respectively. In short, if the given AA data and models are representative, the dual tank contents likely emptied in the first 30 to 40 minutes.

Table 1: Estimated Time to Release Remaining Dual AA Nurse Tank Contents

Description	Estimated AA Volume Remaining		Estimated AA Release Time, minutes		
	gallons	percent	Flow Rate, 50 gpm	1/2 Flow Rate, 25 gpm	1/3 Flow Rate, ~17 gpm
Calculated AA, volume basis	605.1	35.6	12	24	36
Calculated AA, weight basis	653.1	38.4	13	26	39
30 percent of nominal AA load	510	30.0	10	20	31
30 percent of AA tank volume	600	35.3	12	24	36

3.4 Comments

The flow rate and release time estimates described herein are believed to be conservative since additional AA tank plumbing configuration losses encountered in straight, turning, mixing, contracting, and/or expanding flow are not explicitly modeled. That is, actual flow rates may be lower than estimated but not likely higher.[1] The estimated accident release time frame of 30 to 40 minutes is believed to be conservative.

Hose runs with nozzle/coupling inner diameters narrower than the nominal hose diameter or dip tube diameter will restrict the flow rate and may negatively affect the EFV protection if an accidental release occurs (by delaying EFV activation until a higher than intended flow rate has been achieved).

The addition of an EFV downstream of (all) the manifold(s) in a nurse tank trailer configured with two or more tanks supplying AA to one (or more) common manifold(s) would provide a comparable degree of protection against an accidental AA release to that of the no yoke configuration described above. This plumbing configuration requires the most downstream EFV in the single AA supply line to the applicator to have a nominal gpm activation point less than or equal to the most conservative (lowest gpm set point) among the EFVs installed in the AA tanks.

[1] Flow rate losses exist due to friction and are affected by plumbing variables such as length, diameter, turning (elbows), and mixing (tees). Engineering design handbooks can be used to estimate and minimize plumbing configuration flow rate losses.

Based on the factual evidence gathered during this AA accidental release investigation, protection against accidental decoupling of the threaded connection between the AA nurse tank trailer supply and the AA applicator is needed. A simple, fail-safe breakaway connection between the applicator and the nurse tank trailer could be added. Alternatively, a threaded connection protected by a quick connect/disconnect, fail-safe mechanical device such as a "conceptual" cotter pin, spring loaded gear-lock/release, or symmetric ball-bearing anti-rotation barrier could be added.

4.0 ATTACHMENTS

Attachment 1: Anhydrous Ammonia Properties
(Liquid and vapor density versus temperature; pressure versus temperature)

Attachment 2: Anhydrous Ammonia Leak Rate Estimates
(Yoked and no yoke nurse tank plumbing configurations)

Attachment 3: AA Flow Rate versus Nitrogen Application Rate as a Function of Speed
(Applicator width 30 or 60 feet, AA tank pressure 100 psi)

Attachment 1

Anhydrous Ammonia Properties
(Liquid and vapor density versus temperature; pressure versus temperature)

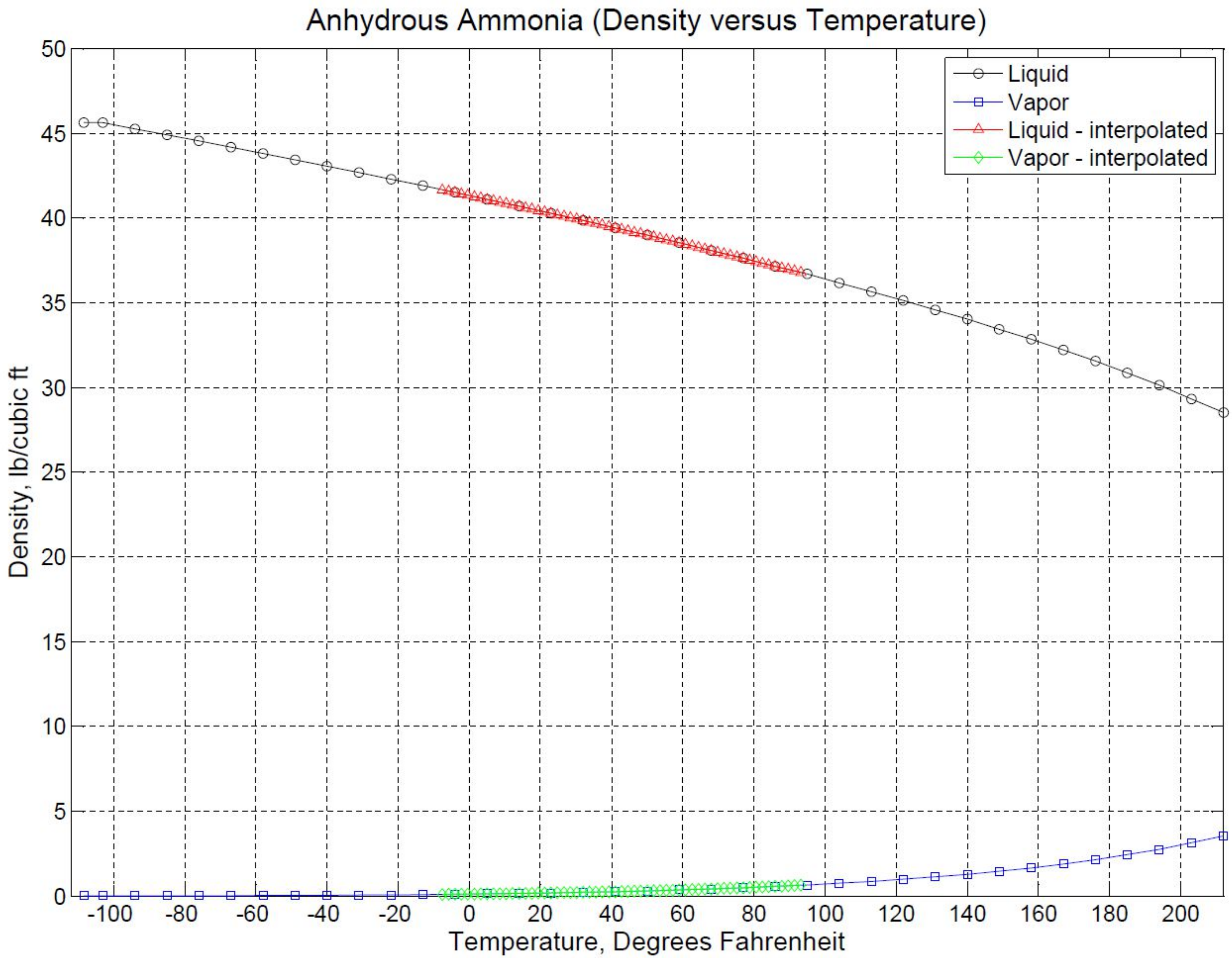

Figure A1.1: Anhydrous ammonia liquid and vapor density as a function of temperature.

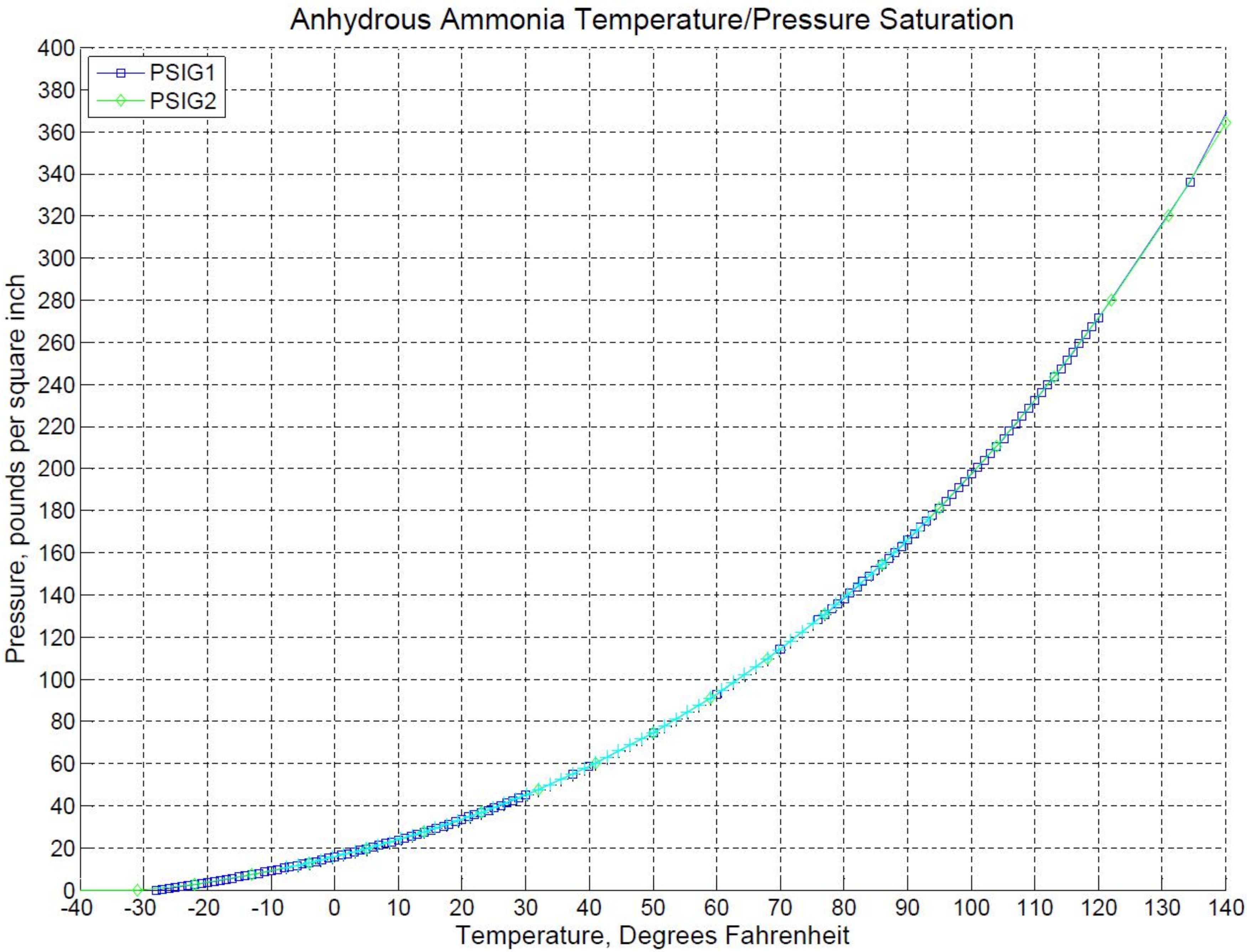

Figure A1.2: Anhydrous ammonia pressure as a function of temperature.

Attachment 2

Anhydrous Ammonia Leak Rate Estimates
(Yoked and no yoke nurse tank plumbing configurations)

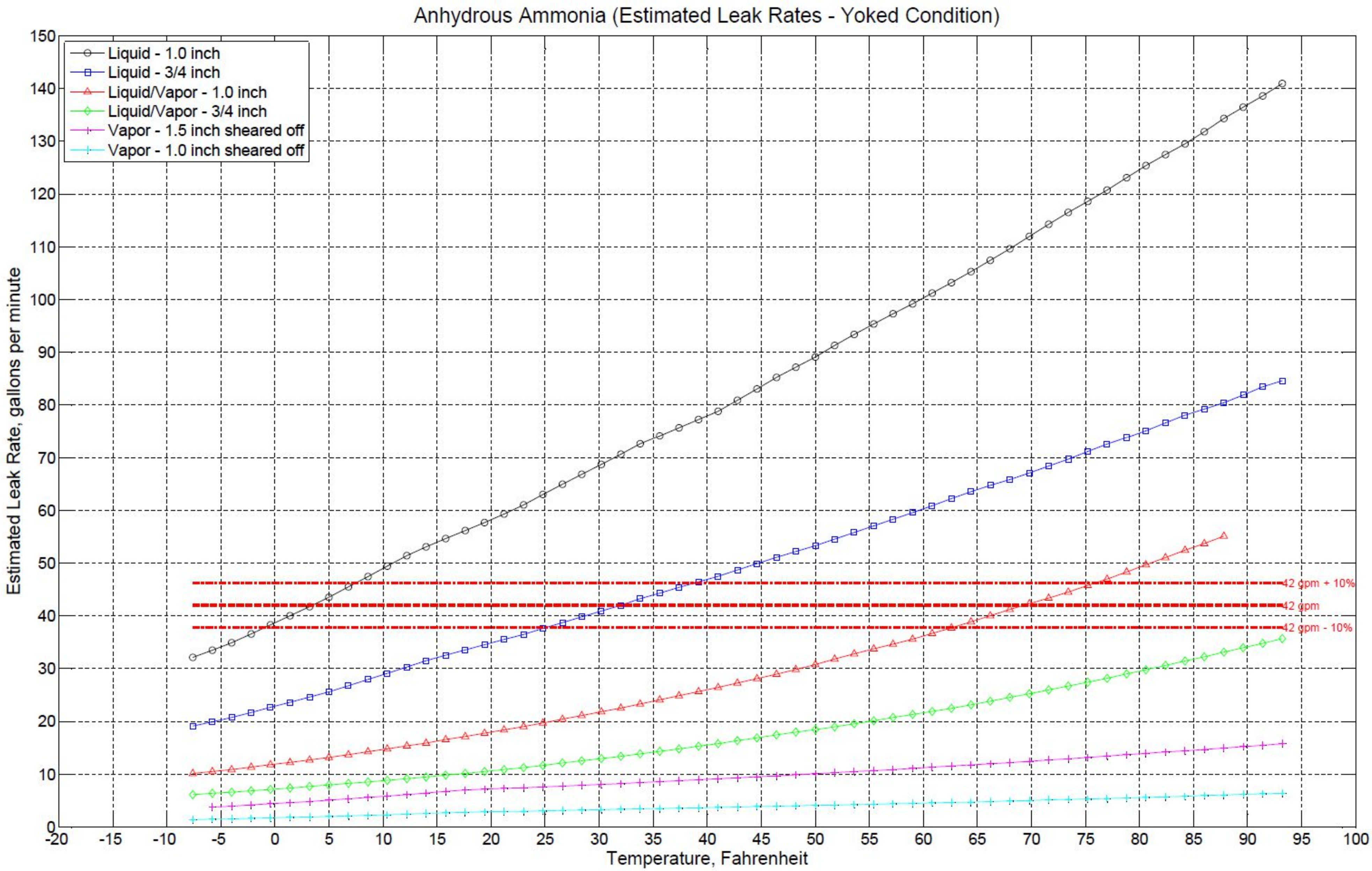

Figure A2.1: Estimated anhydrous ammonia leak rates as a function of temperature, yoked configuration. Example excess flow valve set point 42 gpm ± 10%.

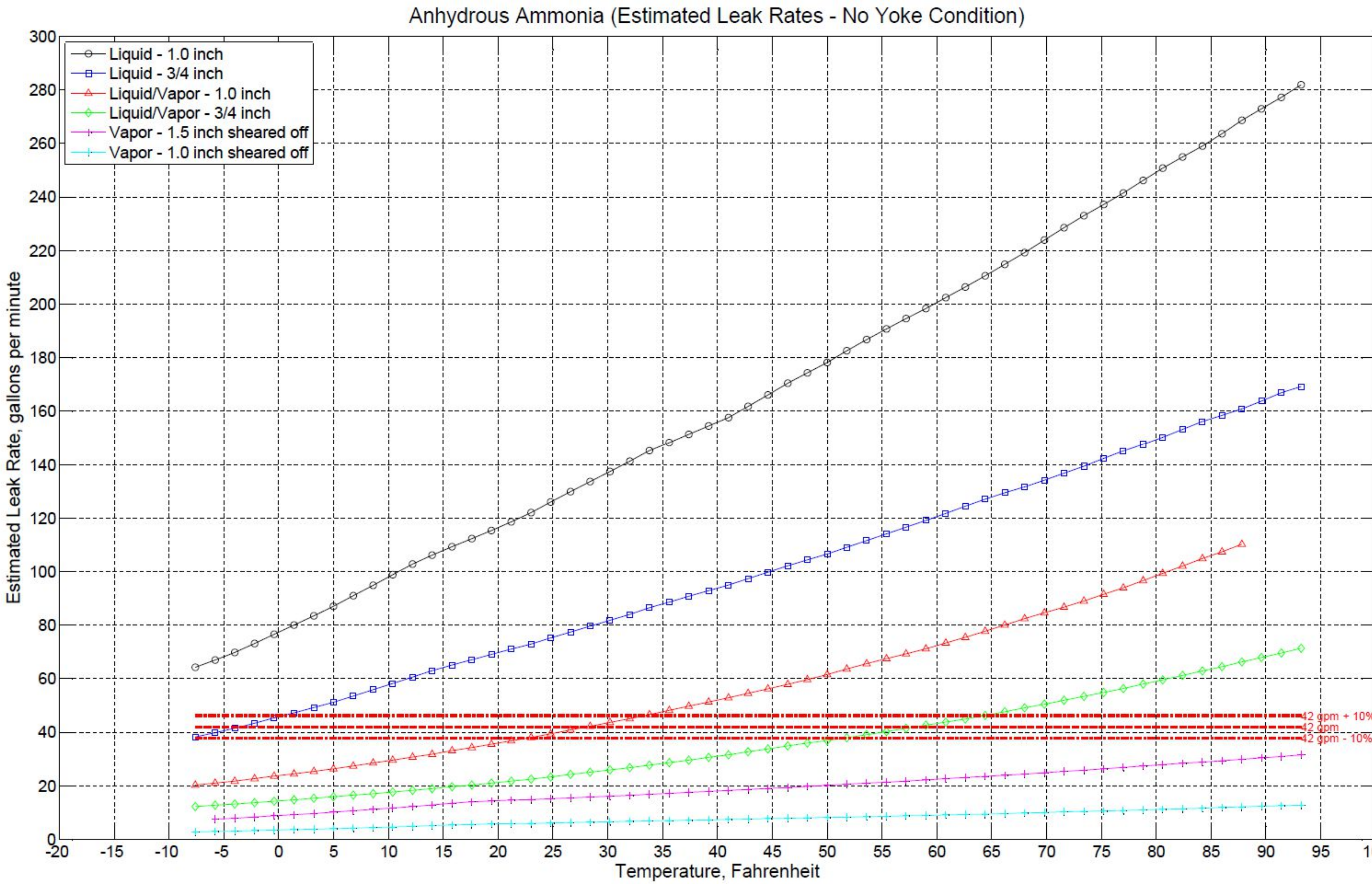

Figure A2.2: Estimated anhydrous ammonia leak rates as a function of temperature, no yoke configuration. Example excess flow valve set point 42 gpm ± 10%.

Attachment 3

AA Flow Rate versus Nitrogen Application Rate as a Function of Speed
(Applicator width 30 or 60 feet, AA tank pressure 100 psi)

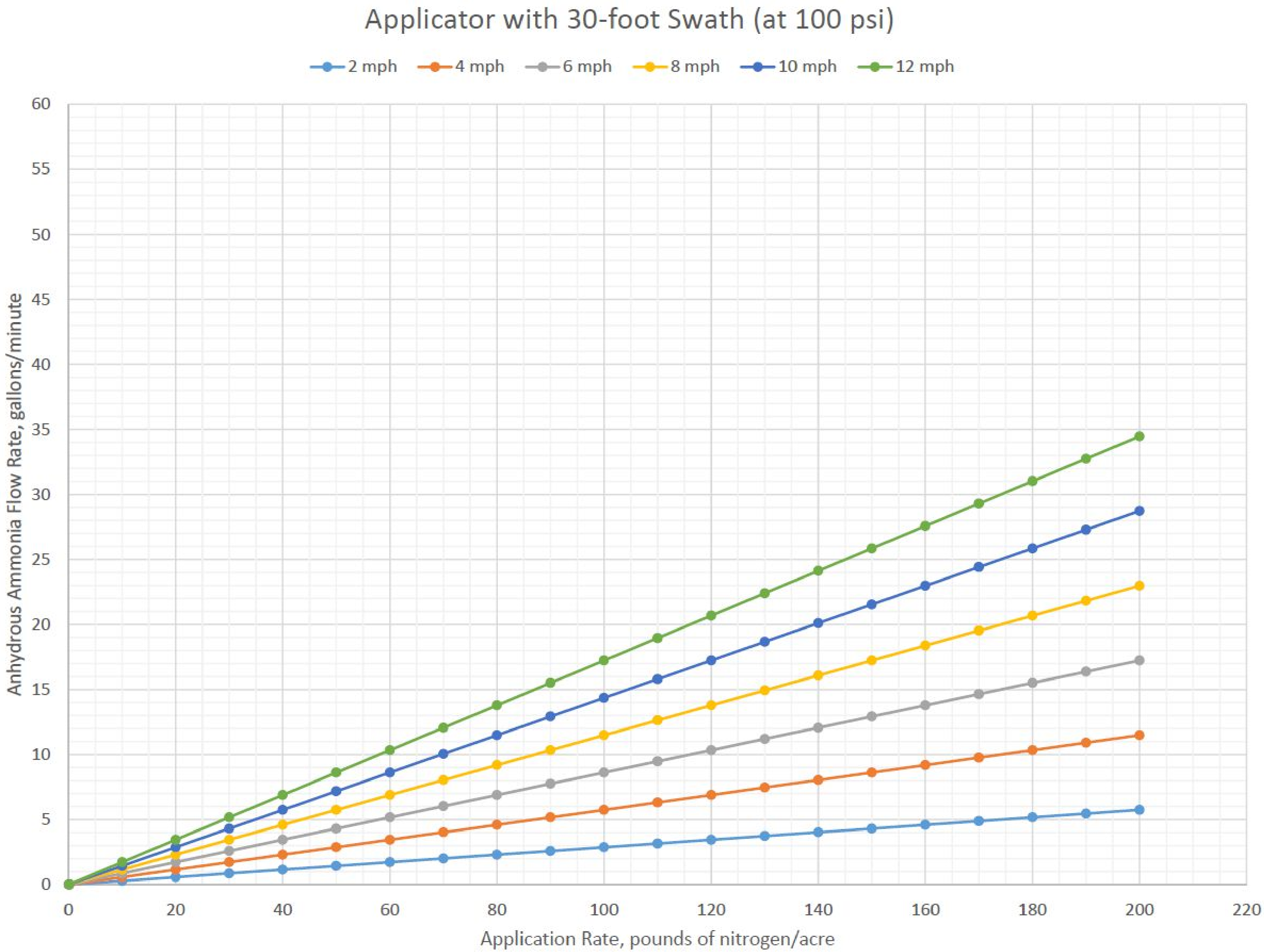

Figure A3.1: Calculated AA flow rate versus nitrogen application rate as a function of speed, applicator width 30 feet, AA tank pressure 100 psi.

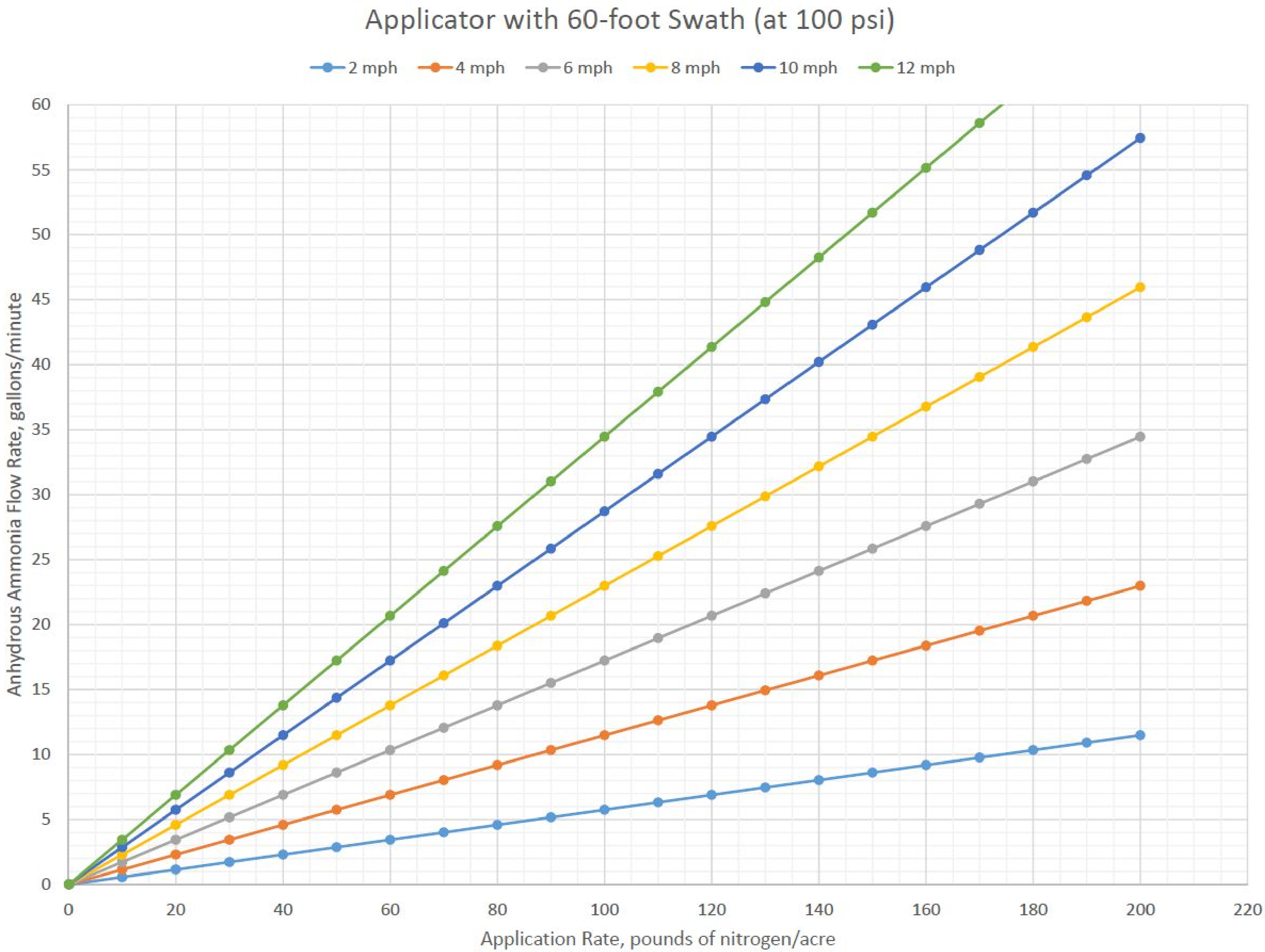

Figure A3.2: Calculated AA flow rate versus nitrogen application rate as a function of speed, applicator width 60 feet, AA tank pressure 100 psi.